Plenary session on the accident at Sayano Shushensk

Summarized by J. Gummer, Session Chairman

In view of the gravity of the accident at Sayano Shushenskya in Russia in August 2009, which involved considerable loss of life, it was decided by the organisers of HYDRO 2010 to hold a plenary session, with a special lecture by Dr E. Bellendir of the VNIIG Institute, St Petersburg, to discuss the causes of the accident and to obtain input from the industry as a whole on the implications of the accident on future design, operation and maintenance of similar hydro plants.

The plenary session was in the form of one major presentation on the accident at the Sayano Shushenskaya plant in Russia, and two more succinct ones on related accidents and events. This was followed by a panel discussion with considerable input from floor. The panel consisted of Dr Evgeny Bellendir, John Gummer, Bryan Leyland and Professor Hermod Brekke. The session was co-chaired by Dr Bellendir and John Gummer.

This paper summarizes the three presentations and the subsequent panel discussion. The summary of Dr Bellendir's presentation on the Sayano Shushenskya accident is necessarily abridged here, and it is intended that a more detailed paper will be presented by Dr Bellendir and his colleagues in a future edition of *Hydropower & Dams*.

At the beginning of the plenary session a full and detailed account of the tragic accident at the Sayano Shushenskya powerplant in Russia was given by Dr Bellendir.

This powerplant, in Khakassia, Siberia, was the world's sixth largest. The powerhouse had ten 640 MW Francis units producing 24 TWh/year, which met 10 per cent of Siberian energy requirements. The plant is on the Yenisei river, and the 245 m-high dam stretches 1 km across the river. The powerhouse is at the toe of the dam, and the gated spillway is on the right side dam crest. The turbines were designed for a rated head of 194 m, and a rated speed of 143 rpm, and the 16 blade Francis runners have an exit diameter of 6.8 m. Guidevane actuation was by individual servomotors and turbine isolation was by means of intake gates, there being no turbine inlet valve. Each turbine was supplied by a dedicated relatively short penstock, flush with the dam's downstream contour.

The first unit began operation in December 1978 and the 10th and last unit came on line in December 1985. Between 2007 and 2011, the plant was modernized and refurbished, during which time controls and protection systems were replaced and a comprehensive distributed control system (DCS) was installed.

Dr E. Bellendir of the VNIIG Institute, St Petersburg, gives full details of the accident at Sayano Shushensk, during the special plenary session in Lisbon. He was warmly applauded for sharing this detailed information with the international hydropower community, so constructive lessons could be learnt from this tragedy.

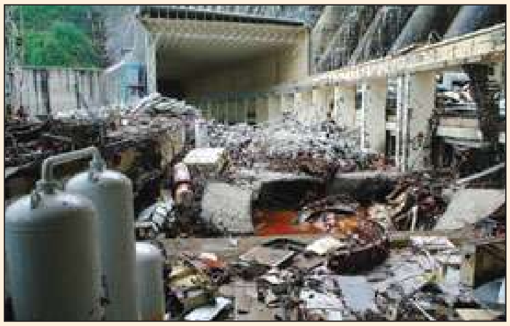
The accident occurred on 17 August 2009 at 08.13 hrs. It was preceded by a fire in a communication room at the nearby Bratsk hydro plant, which resulted in an order to the operators at Sayano Shushensk to use the station for regulation of the electrical grid. Unit 2 was selected as the lead unit for regulation, as it was regarded as the most reliable of the 10 units after its recent maintenance. Units 8 and 10 were operating as base load, Unit 6 was undergoing maintenance and the other six units were following frequency at a higher permanent droop than Unit 2. All the units suffer from substantial draft tube pressure pulsations and associated high vibrations when generating at part load. Vibrations are particularly bad for operation between 250 and 450 MW and consequently the units were normally operated outside of this critical zone.

In its enforced frequency control mode on 17 August 2009, Unit 2 entered the critical zone many times, resulting in considerable vibrations in the unit. According to Dr Bellendir, this type of forced operation in the unstable zones had occurred many times during the life of the units.

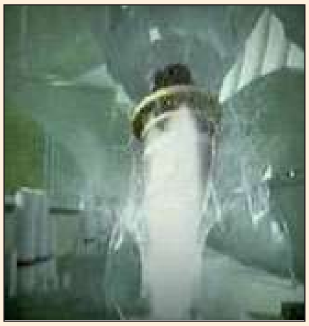
Unit 2 was equipped with vibration monitoring equipment, which had been installed in 2009 during rehabilitation, but unfortutely this equipment was out of service and accordingly considerations and mitigation of high vibration were not part of the operational

The panel, during discussions on lessons learned from the accident at Sayano Shushensk. John Gummer chaired the debate.

Far left: participants at the special plenary session. Nearly 600 delegates attended,



Above left and centre: the Sayano Shushenskaya powerhouse before and after the accident.



Far right: Unit two, weighing more than 1600 tonne, lifts into the air, as the accident occurs.

decisions at the despatch centre. Without doubt, at the time of the accident, head cover and draft tube vibrations were considerably higher than values typically considered acceptable for similar hydro units.

At 08.13 hrs, the head cover of Unit 2 broke away from its restraints. The generator at Sayano Shushensk is mounted on a thrust bearing cone supported on the head cover, and the hydrostatic force under the now free head cover was sufficient to lift the total 1600 tonnes of rotating parts and thrust bearing support cone into the air. Penstock water poured into the now open turbine, flooding the station and causing considerable damage to the other units and to the station services. A transformer exploded, all control to other units was lost and part of the powerhouse roof collapsed. The end result was the complete destruction of Units 2, 7 and 9 and partial destruction of Units 3, 4 and 5.

Dr Bellendir explained that many reasons, including adverse hydraulic transients, higher than design stresses caused by extreme electrical forces, terrorist action, and mechanical failures were considered by the investigating body, but eventually the problem was attributed to failure of the turbine head cover holding bolts which had corroded, loosened and fatigued. Nuts were shown to be missing from six bolts, and pictures were shown of the bolts which had obviously failed in fatigue before the accident.

Repair and replacement of the affected units is now underway. The dam and its foundations were unaffected. Currently Units 6, 5 and 4 are in operation. Dr Bellendir said, and Unit 3 will be on line by the end of this year. Six new units will be installed between 2011 and 2014, and between 2013 and 2014 the repaired units will be removed and new ones installed.

The problems in the powerhouse were exacerbated by subsequent failures in the dam water control systems. These were: the inability to close the intake gates fast and automatically; difficulty in opening the spillway gates; and, failure of the powerhouse drainage pumping system. The reason for the problems with the gates was the complete loss of auxiliary electrical supplies and controls. The pumping system failed because the pumps were not equipped with submersible motors.

Key recommendations

Dr Bellendir recommended that: all power intakes should be automatic and fast closing (maximum closure time of 2 minutes); standby facilities should be available to open spillway gates; all station pumping systems should employ submersible pumps; turbines should not be permitted to run in very rough running regimes; equipment should be regularly inspected for failure and cracks; and, the number of personnel in potential flood zones should be minimal.

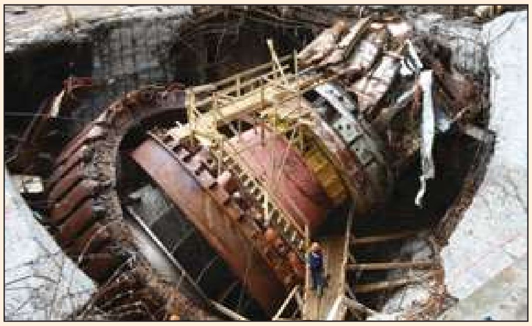
Panel Comments

Dr Bellendir's presentation was followed by an account by Bryan Leyand of a similar accident in Canada. In this case, the four Kaplan units had been more than 40 years old, and two of them had been used extensively for frequency regulation which had resulted in serious hunting to the extent of almost complete closure of the guidevanes on each cycle. Essentially, this had been equivalent to multiple start stops, which had eventually resulted in failure of the head cover bolts and flooding of the station, fortunately in this case with no loss of life.

Bryan Leyland deplored the industry's lack of openness in the case of the Canadian accident, which had never been reported or publicly recorded. Had it been reported, then probably there may have been a general inspection of head cover bolts worldwide, and the accident at Sayano Shushensk could have been avoided. In constrast, Leyland applauded the Russian authorities in their openness in making public the details of the Sayano Shushenskaya powerplant accident, a sentiment audibly shared by all session participants.

Professor Brekke followed with a short description of an accident at a Kaplan powerplant in Norway. This had been caused by the failure of bolts in the runner envelope. These had fatigued as a result of pressure pulsations generated by the passing runner blades. **Professor Brekke emphasized that any bolt load is only taken by about three threads and the stresses in these three threads almost reach the yield strength of the material. When superimposed on such a high stress, any additional dynamic loading on the bolt can be instrumental in promoting fatigue. Such bolt fatigue is exacerbated by the stress concentration in the sharp edged thread and the adverse effects of corrosion on local material properties. Some mitigation can be obtained by increasing the length of the bolts but the only sure solution is regular inspection and bolt substitution, if found by the inspection to be necessary.**

Prof Hermod Brekke of Norway offers his comments and recommendations, and tells of an accident at a Kaplan powerplant in Norway.



Far left: The Sayano Shushensk dam, which did not sustain damage.

Left: Close up view of Unit 2, immediately after the accident.

Chairman's comments and discussion

A lively and interesting open discussion followed which, under the guidance of the co-chairman John Gummer, concentrated on the following aspects highlighted by the accident at Sayano Shushensk:

- design to minimize vibrations in hydraulic machines;
- design of hydro units to minimize the possibility of catastrophic accidents;
- quality Assurance during design, manufacture and erection;
- monitoring of operation to identify potential problems; and,
- maintenance procedures to ensure long term accident free operation.

In his introductory remarks Gummer commented on the problems inherent in ISO 10816-5, the standard which covers permissible vibrations in hydraulic machines. Although limits on the x and y vibrational amplitudes are covered by the code, regrettably it is silent in respect of axial vibrations (z direction). Gummer felt that this needed to be addressed as z direction vibrations were extremely critical, as evident in the Sayano Shushensk accident.

Gummer also queried whether isolating devices such as inlet valves or ring gates should be provided at the turbine inlet, even for large units such as those at Sayano Shushensk. Typically for units with a single relatively short dedicated penstock, turbine inlet valves were not provided and automatic closing of the intake gate was relied upon to protect the unit, he said.

Gummer reflected on the accident at the Dartmouth hydropower station in Australia, which had suffered a guidevane cascade failure resulting from a steel beam imprisoned in the runner. Although the pressure rise resulting from the cascade failure had broken the spiral case, the extent of flooding had been mitigated because the turbine inlet valve had successfully closed.

With respect to maintenance, Gummer raised the question of how often full maintenance requiring complete dismantling of a large unit should be conducted. A period of every seven years, as recommended by one manufacturer, was obviously too short, he felt, whereas 30 years may be too long.

With these introductory remarks Gummer opened the discussion to the floor.

The procedures in evaluating accidents and failures were questioned by one participant. The participant drew on his experience in the aerospace industry, where the first measure, he said, was correction of the immediate defect, the second an immediate search for similar errors and elimination of same, and the third, a full investigation into existing processes to ensure that such errors could never re-occur.

As all three accidents reported by the speakers had occurred as a result of failure of securing bolts, one participant highlighted the critical aspect of informed and ongoing co-ordination between equipment and civil designers. He rightly stated that it is essential for correct design information on both static and dynamic loadings to be passed to the civil designer, to ensure that loads originating in equipment were properly accommodated in the civil works.

With respect to component life and maintenance procedures, Prof. Brekke made the all important comment that with deregulation and the increasing amount of intermittent wind and solar power on electrical systems, many hydro units were being operated in a manner completely different to that for which they had been designed. As opposed to base load generators, hydro units were increasingly called upon to perform multiple start stops, to change load rapidly to regulate system frequency and, as a result, to operate in regions of high vibration. Accordingly a far more intensive inspection regime was required now than adopted previously. Welds of stayvanes, runners, spiral casings, brackets rotor structures and base plates and holding bolts should be non-destructively tested annually, he said. This was particularly important for newer units in which stresses were typically higher than in older ones, he added.

The frequency of dismantling for a complete overhaul should be guided by the results of these inspections. If many cracks are found, then the frequency of overhaul should be increased.

According to Prof. Brekke, if no cracks are found after 100 million cycles of operation, then one could rest at night. If cracks were frequently found and had to be repaired during annual inspections then additional vigilance, possibly involving complete dismantling, would be required.

The changing role of hydro and need for regular inspection was reinforced by a comment from the floor. According to a representative from Andritz

Bryan Leyland of New Zealand described a similar accident which had occurred in Canada, and deplored the fact that details had not been made available to others in the hydro industry.

Hydro, in respect of the fatigue life of some turbine generator components, one start up is equal to a year's operation at best efficiency. This makes regular inspection for cracks and component failure imperative. Professor Brekke emphasized the need for only skilled personnel to be employed in inspections for cracks in hydro components. Equally important is the use of trained professionals in the interpretation of the results of such inspections and in deciding on necessary corrective measures, if any, he said.

There was general agreement that operation of equipment needs to be trended using data from the monitoring systems which are now almost standard in new important plants. The general consensus was that there is no point in having the monitoring if the resulting records are never properly analysed. There was also the suggestion that the state of electrical and mechanical equipment at hydro plants should be periodically audited by an outside body, similar to the now common practice of the auditing of hydro civil structures.

There was a call from one participant for comprehensive risk assessment and the equally important but more embracing procedures of asset management for hydro plants. Risk assessment and asset management are now extensively used in other industries such as oil and gas, and nuclear. Preventative maintenance can be expeditiously managed with risk assessment and needless expensive replacement of parts which have been allowed to deteriorate beyond the state of economic repair can be avoided by adopting appropriate trending procedures. Risk assessment and asset management are particularly relevant for units used for the demanding role of electrical system stability.

The panel was questioned on the merits of continuous vibration monitoring of hydro units, and the value of fatigue analysis of major component parts of the unit. Gummer pointed out that continuous vibration monitoring was used extensively on new important units, and was an integral part of the majority of equipment specifications. Typically monitored were all bearings, generator brackets, turbine head covers and, in some instances, draft tubes cones. Tri-axial vibration transducers were available, or a transducer could be provided for each of the three directions. Gummer again bemoaned the absence of a standard which covered limits for vertical vibrations in hydro units.

Gummer reported that fatigue analysis of important new units was commonly requested by specification and even when it was not, traditionally a manufacturer would conduct this as a matter of course. It was unrealistic and unnecessary to request fatigue calculations for smaller units and in these cases the experience of the manufacturer and past precedence should be relied upon, he said. The theoretical basis for fatigue analysis was well established, and the results obtained were reliable.

The need for detailed and comprehensive operation and maintenance manuals was highlighted by one participant. He rightly stated that many O&M manuals were incomplete or incomprehensible, which could only result in questionable practices over the years of operation of a typical hydro plant. At the start of any project, all manuals, drawings and data should be vetted for completeness and substance, and should be kept up to date as equipment changed or was modified. Similarly, staff should be adequately trained and the operating body should hold ongoing training sessions to cover all conceivable operating emergencies. Emergency measures should be well rehearsed and all operating staff should be aware of exit procedures.

In the context of training, operation and the changing roles of hydro, there was a call for better co-ordination between system controllers and power station staff. Controllers should be aware of the limits of the equipment which they are called upon to operate and that the safety of equipment and operation is paramount. Power station staff should therefore have as much authority as system controllers in determining any operating regime, and should have the right to refuse a command if it puts the generating equipment in jeopardy. There should be an overriding governing body which co-ordinates the various roles and gives priority to the appropriate organization. It is acknowledged that the exigencies of energy supply in a deregulated system are strong and without such established procedures and priorities accidents such as occurred at Sayano Shushensk are all too possible. The example of a small dam in Kazakhstan was mentioned, where commercial demands had taken precedence over safety, with unfortunate results.

Conclusions

Several notable conclusions can be drawn from the description of the accident at the Sayano Shushenskaya powerplant accident, and the subsequent panel discussions and comments from the floor. The first concerns the effect of deregulation and the increasing amount of unpredictable and intermittent wind and solar power in an integrated electrical supply system, both of which are rapidly changing the operating mode of hydro.

Whereas in the past, hydro was typically a base load provider, increasingly it is being used for system regulation and system backup, and as such is encountering multiple start stops, and a propensity for far higher flow-induced vibrations in operation, leading to premature component failure symptomatic of the accident at Sayano Shushensk. Accordingly, at today's hydro plants, greater inspection for component failure is required, together with far more advanced monitoring systems, coupled with proper risk assessment to guide maintenance procedures.

In the same vein, safety of operation should always take precedence over the demands of operation, and there should be strict regulations in force to ensure that this is the case.

The Sayano Shushenskaya powerplant accident also clearly demonstrated the need for automatic failsafe closure of intake gates, such as locally controlled gravity closure, independent of any auxiliary electrical supplies. There should also be a local means to open spillway gates, completely independently of the electrical services supplies. These could be diesel-driven operators, in the case of winched actuated gates, or a diesel-driven pumping set for hydraulic actuated gates.

Operation and maintenance requirements must be well documented, and personnel properly trained to implement the correct procedures, especially those dealing with any conceivable emergency. There could well be a case for external audits of hydro mechanical and electrical equipment and procedures similar to the audits traditionally conducted on hydro civil structures.

Great appreciation was expressed to Dr Bellendir, for his full and frank account of the tragic accident, and it was agreed that the sharing of such information among colleagues in the profession was extremely valuable in preventing future incidents of this kind. The speed with which Russian engineers had researched the causes of the accident, and also made significant progress with remedial work at the site, was also commended. ◊